

Long-range correlations in ALICE at the LHC

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Abstract. Long-range correlations between particles separated by a pseudorapidity gap are a powerful tool to explore the initial stages and evolution of the medium created in hadron-hadron collisions. An overview of the long-range correlations measured by the ALICE detector in pp, p-Pb and Pb-Pb will be presented. This includes analyses of forward-backward, two- and multi-particle correlations with the use of the central barrel and forward detectors.

1. Introduction

Long-range correlations (LRC) are usually considered between particles separated by pseudorapidity gap, that is typically taken to be $|\Delta\eta| \gtrsim 1.0$ in order to suppress contribution from resonances and (mini)jets. LRC can be created only at the early stages of the collision [1] and arise in Color Glass Condensate [2] and string fusion [3] models. On later stages of the system evolution they can be modified by medium and final state interactions (hydrodynamic expansion, energy loss in medium, conservation laws).

How do we extract information about long-range correlations? Different analysis methods are being used, which have different sensitivity to various aspects of physical origin of LRC. Two-particle correlations with large separating η gaps between pairs of particles allows one to get rid of short-range correlations and obtain the correlation pattern, azimuthal profile of which can be decomposed into Fourier series. Another technique, which is sensitive to collective phenomena, uses multiparticle correlations, for example, elliptic flow can be measured by calculating second-order Fourier coefficient v_2 taking 4, 6, 8 or even all particles in event (usually denoted as $v_2\{4\}, v_2\{6\}, v_2\{8\}, v_2\{\text{LYZ}, \infty\}$). Even with 4 particles, non-flow contribution is already suppressed enough, allowing one to measure collective effects during evolution of the system created in a hadronic collision. Forward-backward correlation analysis is another method sensitive to even-by-event fluctuations of number and properties of particle-emitting sources elongated in rapidity.

LRC are measured in Pb-Pb, p-Pb and pp collisions in all major experiments at the LHC. This article collects some experimental highlights on LRC from ALICE.

2. ALICE detector

In ALICE experimental setup, charged primary particles are reconstructed with the central barrel detectors combining information from the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). Both detectors are located inside the ALICE solenoid with a field of 0.5 T and have full azimuthal coverage for track reconstruction within a pseudo-rapidity window of $|\eta| < 0.9$. Charged particle identification (PID) over a broad momentum range is

done using information from the TPC and the Time of Flight (TOF) detectors. The TPC provides a simultaneous measurement of the momentum of a particle and its specific ionisation energy loss (dE/dx) in the gas. The TOF detector surrounds the TPC and provides separation between π -K and K-p up to $p_T = 2.5$ GeV/c and $p_T = 4$ GeV/c, respectively, by measuring the arrival time of particles. VZERO detectors, two forward scintillator arrays with coverage $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$, are used in the trigger logic and for the centrality and reference flow particle determination [4].

3. Two-particle correlations with pseudorapidity gap

The two-particle correlation function $C(\Delta\eta, \Delta\varphi)$ measured in central 0-10% Pb-Pb collisions, is shown in figure 1 (a), demonstrating such structures as “near-side” peak from jets and resonances, “near-side ridge” along $\Delta\eta$ at $\Delta\varphi \approx 0$ and broad away-side structure elongated in $\Delta\eta$ [5]. The *measured* anisotropy of particle production at n -th harmonic order is given by coefficient $V_{n\Delta}$, which can be obtained from triggered, pseudorapidity-separated ($|\eta| > 0.8$) pair azimuthal correlations using expression $\frac{dN^{\text{pairs}}}{d\Delta\varphi} = 1 + 2 \sum_{n=1}^{\infty} V_{n\Delta}(p_T^t, p_T^a) \cos(n\Delta\varphi)$, where p_T^t and p_T^a are transverse momenta of trigger and associated particles.

In very central events 0-2% (figure 1, b), the away side exhibits a concave, doubly-peaked feature ($V_{3\Delta} > V_{2\Delta}$), that is usually attributed to fluctuations in initial state geometry which can generate higher-order flow components. It was checked whether a set of single-valued points $v_n(p_T)$ can be identified that describe the measured long-range anisotropy via the relation $v_n(p_T^t)v_n(p_T^a) = V_{n\Delta}(p_T^t, p_T^a)$. If so, $V_{n\Delta}$ is said to factorize into single-particle Fourier coefficients. These pair anisotropies are found to approximately factorize into single-particle harmonic coefficients for $p_T^a < 4$ GeV/c. This factorization is consistent with the picture of collective response of the medium to anisotropic initial conditions.

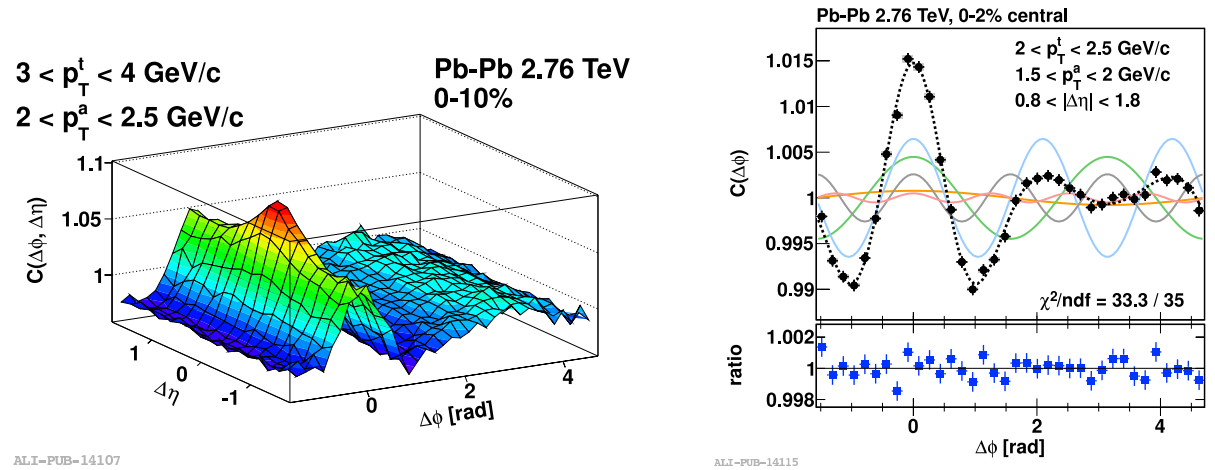


Figure 1. Left: two-particle correlation function $C(\Delta\eta, \Delta\varphi)$ for central 0-10% Pb-Pb collisions at 2–4 p_T range. Right: $C(\Delta\varphi)$ for particle pairs at $|\eta| > 0.8$ in most central 0-2% events. The Fourier harmonics for V_1 to V_5 are superimposed in color [5].

4. v_2 for identified particles in different p_T ranges

Elliptic flow (v_2) in Pb-Pb collisions was measured with the Scalar Product method, which is a two-particle correlation technique, using a pseudo-rapidity gap of $|\eta| > 0.9$ between reference particles in VZERO scintillators and the identified hadrons of interest within TPC [6]. Dependence of v_2 on p_T in centrality class 10-20% is shown in figure 2 (a) for π , K, p, Λ , ϕ , Ξ and Ω . Shift of the $v_2(p_T)$ dependences towards higher p_T is observed for heavier particles due

to interplay between elliptic and radial flow (“mass ordering”) up to 3 GeV/ c . Mass ordering is stronger in most central collisions because of stronger radial flow. Particles with $p_T > 3$ GeV/ c tend to group according to their type, i.e. mesons and baryons (except for ϕ meson). In this range of p_T , quark coalescence was suggested to be the dominant hadronization mechanism, however, ALICE data exhibit deviations from the number of constituent quark (NCQ) scaling at the level of $\pm 20\%$.

Mass ordering was observed also for π , K and p in p-Pb collisions, when v_2 was extracted from two-particle correlations in high-multiplicity events after subtraction of correlations in low multiplicity events (figure 2, b) [7]. Qualitatively similar picture in p-Pb as in Pb-Pb collisions suggests common origin of long-range correlations in A-A and in smaller systems. This question currently is under intensive debates and investigation.

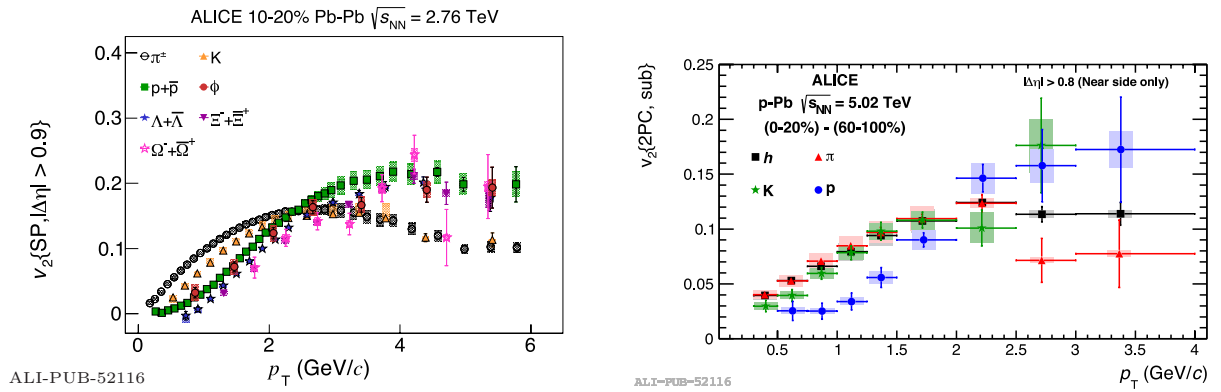


Figure 2. The p_T -differential v_2 for different particle species in centrality class 10-20% of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [6] (left) and in 0-20% class with subtracted 60-100% class of p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [7] (right).

5. Forward-central two-particle correlations in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Further studies of long-range correlation structures were performed in p-Pb collisions using inclusive muons from muon spectrometer as trigger particles (with $0.5 < p_T < 4$ GeV/ c , $-4 < \eta < -2.5$) and associated charged particles in ITS+TPC ($|\eta| < 1$, $0.5 < p_T < 4$ GeV/ c) [8]. Reconstructed muons mainly originate from weak decays of π , K and mesons from heavy flavor (HF) decays.

Figure 3 (a) shows yield of associated particles in $(\Delta\eta, \Delta\varphi)$ coordinates in 0-20% event classes after subtraction of 60-100% class. It can be seen that near-side ridge extends up to $|\Delta\eta| \approx 5$ and it decreases from $\eta = -1.5$ to $\eta = -5.0$. Analysis was done at both beam directions p-Pb and Pb-p, and, assuming factorization of the Fourier coefficients at central and forward rapidity, extracted v_2 coefficients were found to be larger by 16 ± 6 when muons are measured in Pb-going direction, rather than p-going (figure 3, b). Calculations using AMPT event generator showed qualitatively similar behavior at low p_T .

6. Forward-backward multiplicity correlations in pp collisions

The forward-backward (FB) multiplicity correlations were previously studied in a large number of colliding systems. These correlations are characterized by the correlation strength b_{corr} . ALICE performed analysis of FB multiplicity correlations in pp collisions in a soft range of p_T (0.3–1.5 GeV/ c) at $\sqrt{s} = 0.9, 2.76$ and 7 TeV [9]. Figure 4 demonstrates behaviour of b_{corr} as a function of separating η gap between forward and backward windows. The correlation strength drops with η gap since short-range contribution reduces, also b_{corr} values increase with collision energy.

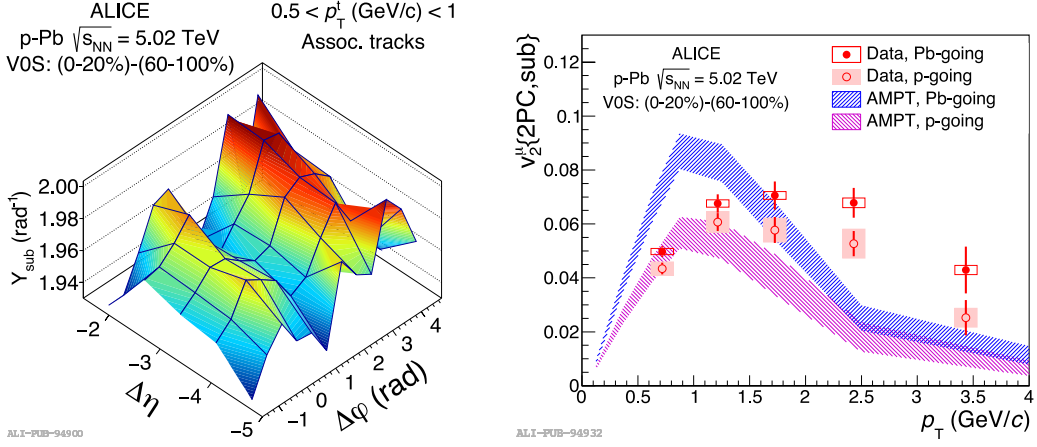


Figure 3. Left: associated yield per trigger particle in 0-20% event classes after subtraction of 60-100% class as a function $\Delta\eta$ and $\Delta\phi$ for muon-track correlations in p-Pb. Right: the $v_2^{\mu}\{2\text{PC,sub}\}$ coefficients from muon-tracklet correlations in p-going and Pb-going directions [8], the data are compared to model calculations from AMPT.

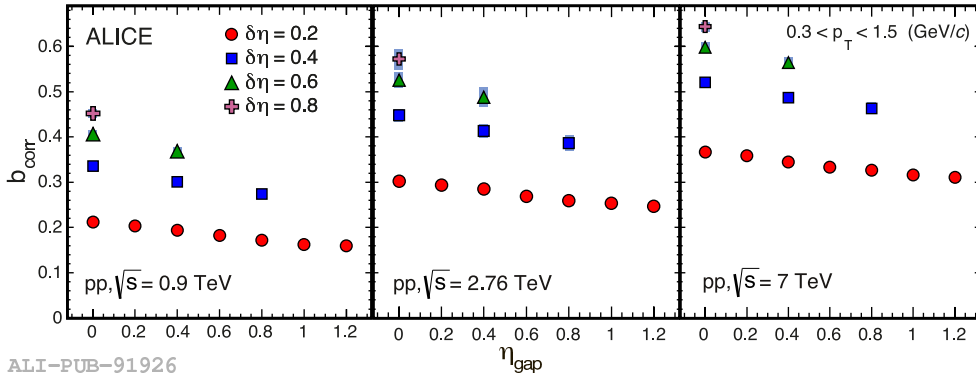


Figure 4. Forward-backward correlation strength b_{corr} as function of η_{gap} and for different window widths $\delta\eta=0.2, 0.4, 0.6$ and 0.8 in pp collisions at $\sqrt{s} = 0.9, 2.76$ and 7 TeV [9].

In order to get more insight into particle production mechanisms, conventional analysis of the FB multiplicity correlations between two η -intervals was extended into azimuthal dimension. Figure 5 for two energies $\sqrt{s} = 0.9$ and 7 TeV shows that correlation pattern in η - ϕ space can be split into short-range peak and *non-zero plateau* which spreads over all studied η - ϕ separations of FB windows (underlying long-range correlation). This non-zero plateau is found to increase with the collision energy. In a simple model of independent particle emitters [10] this rise is attributed to increase of fluctuations in number of independent sources (strings).

7. Final remarks

Long-range correlations provide insights into initial stages and details of the evolution of hadronic collisions. The correlations are being studied at ALICE in pp, p-Pb, Pb-Pb collisions by several analysis methods. Two-particle correlations with separating η gap reveal azimuthal correlation structures, like double-hump shape in central Pb-Pb collisions. Clear mass ordering at $p_T \lesssim 3$ GeV/c in p-Pb, Pb-Pb events is consistent with the picture of hydrodynamic expansion of the medium in A-A collisions, and also states the question about origin of the flow in small

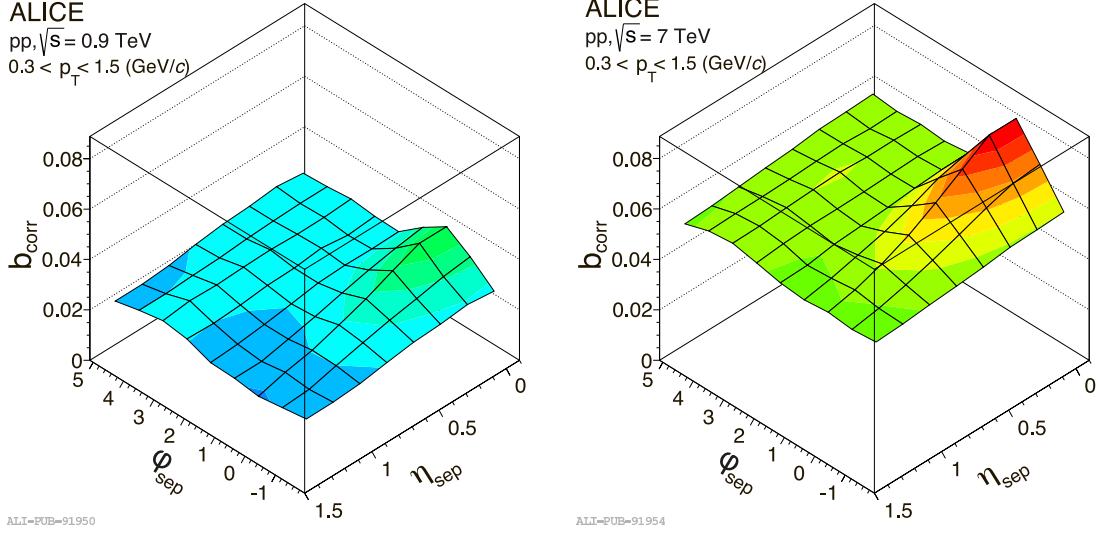


Figure 5. 2D representation of b_{corr} values in forward-backward η - ϕ window pairs with widths $\delta\eta=0.2$ and $\delta\phi=\pi/4$ at $\sqrt{s} = 0.9$ TeV (left) and at $\sqrt{s} = 7$ TeV (right) [9].

systems. Analysis of muon-hadron correlations in p-Pb collisions shows that long-range double-ridge persists up to $\Delta\eta \approx 5$. Forward-backward correlations in pp provide access to fluctuations in number and properties of particle-emitting sources.

With the limited central barrel acceptance for tracking, ALICE can measure long-range correlations with other, non-tracking detecting systems. For example, η -dependence of the anisotropic flow in Pb-Pb collisions was measured recently with two- and four-particle correlations using forward detectors in a range $-3.5 < \eta < 5$ [11]. After upgrade in 2019–2020, ALICE will have a new Inner Tracking System with larger η coverage and also a new Muon Forward Tracker (MFT). Combined ITS+MFT acceptance $-3.6 < \eta < 1.2$ will significantly extend possibilities to study LRC of charged particles.

Acknowledgements

This work is supported by the Saint-Petersburg State University research grant 11.38.242.2015.

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